Developing a Predictive Capability for Bioluminescence Signatures

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LONG-TERM GOALS

Bioluminescence represents an operational threat to naval nighttime operations because of the risk of detection due to flow stimulation of naturally occurring plankton. In the littoral, the primary sources of bioluminescence are dinoflagellates, common unicellular plankton that exhibit a wide range of abundance. Dinoflagellate bioluminescence is stimulated by flow stresses of different origins that have sufficient magnitude to cause cell deformation, such as in high shear flows that are created in boundary layers around swimming animals, in ship wakes, and in breaking surface waves, leading to spectacular displays of bioluminescence during periods of high cell abundance. The oceans can be considered a luminescent “minefield” where bioluminescence is stimulated by flow disturbance. The bioluminescent “signatures” of some swimming fish are distinct enough to differentiate species; nocturnally foraging predators may use bioluminescent wakes to locate their prey.

The bioluminescence signature of a moving object depends on the bioluminescence potential of the organisms (related to their species abundance), the volume of the high shear stress regions associated with boundary layer flow and separated flow in the wake, and its detectability from a surface observer based on radiative transfer of the light through the water and surface interface, as well as surface ambient light conditions. We are interested in predicting bioluminescence signatures, specifically in developing the capability to model flow stimulated bioluminescence and applying the model to a

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14. ABSTRACT

Bioluminescence represents an operational threat to naval nighttime operations because of the risk of detection due to flow stimulation of naturally occurring plankton. In the littoral, the primary sources of bioluminescence are dinoflagellates, common unicellular plankton that exhibit a wide range of abundance. Dinoflagellate bioluminescence is stimulated by flow stresses of different origins that have sufficient magnitude to cause cell deformation, such as in high shear flows that are created in boundary layers around swimming animals, in ship wakes, and in breaking surface waves, leading to spectacular displays of bioluminescence during periods of high cell abundance. The oceans can be considered a luminescent ?minefield? where bioluminescence is stimulated by flow disturbance. The bioluminescent ?signatures? of some swimming fish are distinct enough to differentiate species; nocturnally foraging predators may use bioluminescent wakes to locate their prey.

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computational fluid dynamics model of the flow field of a moving object, and exploring mitigation strategies that reduce the bioluminescence signature to reduce the threat of detection of moving underwater vehicles.

OBJECTIVES

An extremely challenging goal is the need to predict the intensity and spatial "footprint" of bioluminescence signatures of naval relevance. Advances in computational fluid dynamics (CFD) led by PI Hyman make it possible to model the flow around a moving object, and now a new bioluminescence stimulation (BIOSTIM) model developed by PI's Deane and Stokes (Deane and Stokes 2005) provides an initial capability to estimate bioluminescence levels as a function of flow properties, specifically fluid shear stress, which we have previously shown to be the flow property most closely correlated with flow-stimulated bioluminescence in primarily laminar flows (Latz et al. 1994; Latz et al. 2004a; Latz et al. 2004b; Latz and Rohr 1999; Maldonado and Latz 2007).

The primary scientific objectives of this project are to: (1) perform "calibration" experiments to determine the relationship between bioluminescence stimulation and fluid shear stress; (2) update the BIOSTIM model based on the calibration experiments results to include a high shear stress stimulation component; (3) evaluate computational approaches using Reynolds-averaged Navier-Stokes (RaNS) and Direct Numerical Simulation (DNS) solvers, to determine which is more suitable for bioluminescence predictions; (4) validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are characterized using CFD models, so that model predictions of bioluminescence intensity can be compared to experimental results; and (5) couple the BIOSTIM and CFD models to provide a unique flow visualization tool, which can be used to predict bioluminescence signatures for flow fields of naval interest.

APPROACH

Experimental work is done with cultures of the dinoflagellate *Lingulodinium polyedrum* (Stein) Dodge 1989, a model species because it is extremely well studied in terms of general biology and flow stimulation of bioluminescence.

Task 1: Fully developed pipe flow is a useful experimental approach for examining the relationship between bioluminescence stimulation and flow because: (1) it offers a wide range of laminar and turbulent flow stimuli, (2) the flow field is fully characterized based on simple measurements of volumetric flow and pressure drop, (3) organisms experience the flow field for only a brief time period and are continuously replaced, (4) significant depletion of bioluminescence does not occur upstream of the region of light measurement, and (5) bioluminescence trajectories can be imaged within the flow field. We have successfully used pipe flow to examine the relationship between bioluminescence stimulation and fluid shear stress for laminar flow (Latz et al. 2008; Latz et al. 2004a; Latz et al. 2004b; Latz and Rohr 1999; Maldonado and Latz 2007; Rohr et al. 2002; Rohr et al. 1998); we now focus on turbulent flow.

Task 2: The current probabilistic model for bioluminescence stimulation (BIOSTIM) contains three components to allow for: (1) direct stimulation by fluid shear stress, (2) rate-of-change of fluid shear stress, and (3) a memory term to allow for cell desensitization resulting from prolonged exposure to stimulation. The model is based on the fundamental assumption that over any small time interval there is a small but finite chance that a cell will flash, which depends on these three factors. This study considers the case of intense but brief stimulation lasting for no more than a few seconds. In this case we do not have to account for the effects of cell desensitization (von Dassow et al. 2005) and cell memory, greatly simplifying the experiments and analysis required to model the effects of turbulence.

Task 3: The overall objective of this study is to obtain bioluminescence stimulation data under conditions of high shear stress to feed into the BIOSTIM model, which then is incorporated into CFD models to predict bioluminescence signatures created by bodies traveling in or on the ocean. The most generally applicable simulation techniques are algorithms that solve the Reynolds-averaged Navier-Stokes (RaNS) equations and compute the ensemble-averaged velocities, as well as turbulent energy and energy dissipation fields throughout a given flow, allowing an estimation of local (averaged) turbulent shear stress. The RaNS algorithm to be used in the proposed task is CFDSHIP-IOWA, a well-documented algorithm previously used by PI Hyman and verified with full-scale tests with many types of naval ships. However, such algorithms cannot resolve the very small scales that are responsible for bioluminescent stimulation. The action of such small scale turbulence is approximately characterized by the averaged energy dissipation rate – a modeled quantity. In contrast, the BIOSTIM model, as currently written, is most appropriate for use in a Direct Numerical Simulation (DNS) solver. DNS solutions capture all relevant length and temporal scales in the flow including bioluminescence stimulatory scales (these are in the Kolmogorov or inertial range, depending on Reynolds number). To accomplish this, however, the solvers require extremely fine grids – grids that become too large when flow simulation of model-scale vehicles is attempted and far too large to be considered for full-scale naval vehicles. Therefore the new bioluminescence stimulation model developed in Task 2 will accept the ensemble-averaged flow data produced during a practical flow simulation as a means of determining stimulation probability.

Task 4: Validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are modeled using computational fluid dynamics (CFD), so that model predictions of bioluminescence intensity can be compared to experimental results. A critical part of this project is to validate the updated BIOSTIM model to determine how predicted results compare to experimental measurements with independent flow fields. The BIOSTIM model is coupled to the CFD model of a body mounted in a flow field to predict levels of stimulated bioluminescence. A new test flume will be designed and fabricated for the validation tests. Bioluminescence will be measured with a digital low-light digital camera system to quantify light levels in the boundary layer and wake regions. The experimental results are then compared to the coupled BIOSTIM-CFD model predictions.

WORK COMPLETED

The PIs held a project team meeting at Scripps during September 2009 to discuss the project plan and strategy for integrating the computational and experimental activities. The first goal is to perform diret numerical simulations (DNS) of the flow field associated with a sphere for velocities of 0.5 and 1 m/s, to obtain 2D maps of local fluid shear stress. The current BIOSTIM model will be incorporated into the DNS results to predict levels of stimulated bioluminescence; these predictions will be compared to existing bioluminescence images of a sting-mounted sphere moving at the same speeds in a flume and imaged with a digital low-light camera.

The second immediate goal is to assemble a measurement system for evaluating the flashes of individual dinoflagellate cells using a high-speed detection system. The current photon-counting detection system is limited to 10 ms integrations, adequate for most situations but too coarse for precise measurements of the time course of flash kinetics. The new high-speed photomultiplier system will consist of an analog detector rather than a photon-counting detector, allowing high-frequency sampling at sub-ms time scales. These more precise measurements will be important in modeling the flash kinetics. The measurement system will also be used to evaluate flash properties in multiple flashes per cell (Task 1).

Task 4. The experimental flume for validation tests was designed and fabricated by a team of UCSD mechanical engineering students (Joshua Cheng, Evan Coons, Casey Fukunaga, Steven Luu) in the Jacobs School of Engineering as part of their capstone industry-sponsored design course (MAE 156). The 200 gal head tank is coupled to a 4 in diameter acrylic tube in which the test body is sting mounted. Flow is controlled by a downstream metering valve. High flow rates of 25 L/s and speed of 4 m/s were achieved by having a 10 m head using a 50 foot length of fire hose. Flow is limited by the pressure head and frictional losses; the greatest frictional losses were due to the friction in the fire hose (62%) and the T-bend (16%).

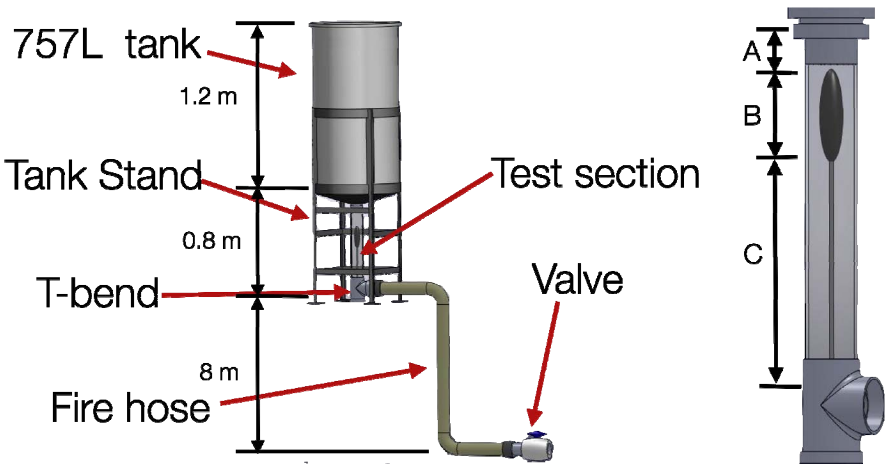

Figure 1. Schematics of the experimental flume for validation tests. (Left) View of overall design, showing the head tank and tank, test section of 4 inch diameter acrylic pipe coupled to 4 inch diameter fire hose, and the metering valve. (Right) View of test section, showing a test body sting mounted in the acrylic pipe. Not shown is that the pipe is surrounded by a rectangular viewing chamber to minimize optical distortion during bioluminescence imaging.

Automated analysis software was written that provides key flash properties (flash rate, flash amplitude distributions, and flash decay time distributions) from existing time series data using an integrating photomultiplier tube detector. This software has significantly reduced the time required for single flash analysis of experimental data.

RESULTS

Existing data from an earlier study of bioluminescence stimulated by rising bubbles has been incorporated into the stimulation model. This modification has allowed us to quanititatively interpret turbulent energy dissipation rates within bubbly, two-phase flows. The rates obtained are consistent with global dissipation rates estimated with independent techniques.

IMPACT/APPLICATIONS

Project results will enhance DoD capability for predicting levels of bioluminescence associated with surface and underwater vehicles of naval interest. The BIOSTIM model can be used in applications involving swimmer delivery vehicles and other submersible platforms, as well as torpedoes and other high-speed objects. The breakthrough in providing this capability is the development and application of the BIOSTIM model, developed by Deane and Stokes, that forms a theoretical basis for studying the relationship between flow stimulation and the bioluminescence response. The BIOSTIM model, when coupled to computational hydrodynamics models that provides values of shear stress for a given flow field, allows for predictions bioluminescence intensity for a given level of bioluminescence potential, either measured directly or obtained from the NAVOCEANO METOC database once a transfer function between the flow agitator and flow field is known.

A coupled BIOSTIM-CFD model introduces a new predictive capability for estimated bioluminescence signatures. A validated model can then be verified with full-scale experiments with surface ships and underwater vehicles of naval interest. In situations where field tests are not possible, once a transfer function between the flow agitator and flow field is known, it can be used with the NAVOCEANO METOC database of bioluminescence potential measurements to predict bioluminescence signatures in essentially any oceanic region. The Non-acoustical Optical Vulnerability Assessment Software (NOVAS) being developed by NRL (Matulewski and Mcbride 2005) has a placeholder in which the coupled BIOSTIM-CFD model can be incorporated into the nighttime visibility assessment component.

RELATED PROJECTS

The objectives of this project are complimentary and related to the objectives of an NSF funded program to better understand energy dissipation within breaking wave crests using the bioluminescent flash response of dinoflagellates as a flow visualization tool.

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